



Integrating Life-cycle Assessment into Transport Cost-benefit Analysis

Manzo, Stefano; Salling, Kim Bang

Published in:
Transportation Research Procedia

Link to article, DOI:
[10.1016/j.trpro.2016.05.064](https://doi.org/10.1016/j.trpro.2016.05.064)

Publication date:
2016

Document Version
Publisher's PDF, also known as Version of record

[Link back to DTU Orbit](#)

Citation (APA):
Manzo, S., & Salling, K. B. (2016). Integrating Life-cycle Assessment into Transport Cost-benefit Analysis. In *Transportation Research Procedia* (Vol. 14, pp. 273-282). Elsevier. *Transportation Research Procedia* <https://doi.org/10.1016/j.trpro.2016.05.064>

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

6th Transport Research Arena April 18-21, 2016



Integrating life-cycle assessment into transport cost-benefit analysis

Stefano Manzo ^{a,b,*}, Kim Bang Salling ^a

^aDepartment for Transport, Technical University of Denmark, Kgs. Lyngby 2800, Denmark

^bGlobal Decision Support Initiative Centre, Technical University of Denmark, Kgs. Lyngby 2800, Denmark

Abstract

Traditional transport Cost-Benefit Analysis (CBA) commonly ignores the indirect environmental impacts of an infrastructure project deriving from the overall life-cycle of the different project components. Such indirect impacts are instead of key importance in order to assess the long-term sustainability of a transport infrastructure project. In the present study we suggest to overcome this limit by combining a conventional life-cycle assessment approach with standard transport cost-benefit analysis. The suggested methodology is tested upon a case study project related to the construction of a new fixed link across the Roskilde fjord in Frederikssund (Denmark). The results are then compared with those from a standard CBA framework. The analysis shows that indirect environmental impacts represent a relevant share of the estimated costs of the project, clearly affecting the final project evaluation. Additionally, they can significantly modify the weight of the different components of the overall project costs – evidently becoming a significant part of the estimated construction cost. Therefore, the suggested approach guarantees a higher quality of information thus providing decision makers with a more thorough insight of the environmental impact of the project.

© 2016 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license

(<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

Peer-review under responsibility of Road and Bridge Research Institute (IBDiM)

Keywords: life-cycle assessment; cost-benefit analysis; sustainability; transport models; decision support modelling

* Corresponding author. Tel.: +45 45251554.

E-mail address: stman@transport.dtu.dk

1. Introduction

Based on the outcome from the Brundtland report (UN, 1987), Holden et al. (2013) derived four main dimensions of sustainable development: satisfaction of human needs, intra- and intergenerational equity and long-term ecological sustainability. Having the latter dimension in mind, it can be argued that traditional transport project evaluation frameworks commonly fail to provide decision makers and stakeholders with a complete picture of the full environmental costs deriving from the implementation of transport projects. In fact, while the direct environmental costs, such as air pollution from vehicles operation, are normally included in the project evaluations, the indirect environmental costs, such as the energy and emissions associated with vehicle manufacturing, are usually not. Herein, the indirect environmental costs are identified as those deriving from the life-cycle of the project components, commonly quantified through Life-Cycle Assessment (LCA) techniques. In synthesis, LCA is the assessment of the environmental impact of a given product or process throughout its lifespan (ISO 14040, 2006) and it is mainly used to compare different products or processes whereafter the one with the least ecological footprint can be prioritised. The standard LCA framework has four steps and includes goal definition and scoping, inventory analysis, impact assessment and interpretation (Kloepffer, 2008). The environmental impact is assessed with a holistic approach spanning throughout the entire lifespan of the product or process, including raw material extraction and processing, manufacture, distribution, use, maintenance, recycle and disposal. LCA analyses are based on the information provided by life-cycle inventories, where the environmental impacts of a product or a process are first defined through a system modelling approach and then quantified. Eventually, the aim of LCA is to quantify the overall life-cycle environmental impact of a product or process, in terms of both resources taken from and released to the ecosystem.

The use of LCA methods in transport studies is primarily seen by the authors as a tool to inform decision makers and help as they develop strategies to meet environmental and sustainability goals. Part of the existing literature focuses on the different environmental impacts deriving from different transport modes. Chester and Horvath (2009) use LCA to analyse passenger transport in the US considering car, buses, trains and airplanes. They find that life-cycle energy inputs and greenhouse gas emissions increase the vehicle operating costs from 31% (air) to 155% (rail). Chester et al. (2010a) make a comparative energy and emission transport LCA for three US metropolitan regions. The results show that the inclusion of life-cycle environmental impacts results in significant increases in terms of energy consumption and emissions, up to 20 times that of vehicle operation for all modes. Some of the studies on the field use an integrated approach combining transport and land use frameworks. Kimball et al. (2013) implement such an approach to quantify long-term impacts from land use and public transport (transit oriented) policies. They highlight how environmental effects from building construction, vehicle manufacturing and energy feedstock are significant.

LCA is also used in the literature to quantify the indirect environmental costs of building transport infrastructure projects. Park et al. (2003) use a LCA to investigate indirect costs of highway constructions, where environmental impacts are estimated based on the energy consumption. The results show that the highest amount of energy is used in the manufacturing stage of construction materials, followed by maintenance and repair stages. Chester and Horvath (2010b) apply LCA on transport modes in the California corridor, comparing existing modes with the high speed rail system planned to be constructed by the State of California. The results show that, due to the required new infrastructure building process, the high-speed rail connection may or may not produce fewer environmental burdens depending on the actual future ridership. Thoft-Christensen (2011) uses LCA to analyse a motorway infrastructure case study. The results demonstrate that design and maintenance costs of a new infrastructure can be expected to be higher than those of repair or enhancement of an existing one. Chester et al. (2013) implement a LCA to analyse near-term and long-term sustainability effects of transport modal shift from private to public transport (transit oriented). The results show that the life-cycle of the infrastructure, vehicle and energy production components significantly increases the footprint of each mode, although authors argue that emerging technologies may reduce the impacts.

Despite transport LCA studies clearly indicate the importance of the indirect environmental impacts in assessing transport sustainability, with the partial exception of Thoft-Christensen (2011) no attempts have been made to define the effect of integrating LCA into standard transport Cost-Benefit Analysis (CBA). Building on the existing literature, the aim of the present study is to fill this gap by, first, outlining a framework combining LCA and CBA

and, second, implementing a case study to compare the results from a standard CBA and the suggested framework. As first step, a LCA module is integrated into the UNITE-DSS model (Salling and Leleur, 2015), a tool developed to implement and assess transport infrastructure projects CBA. Then, a case study referring to the planned construction in Frederikssund (Denmark) of a new road bridge across the Roskilde Fjord is analysed. The effects of the new infrastructure on the overall Danish transport system are estimated by using the Danish National Transport Model (NTM), an activity-based model meant to establish a unified reference model for transport policy analyses and project evaluations in Denmark (Rich et al. 2010). The results from the NTM, in terms of changes in traffic and derived measures, are then used for a CBA comparative exercise. The Frederikssund bridge project is evaluated first by using the UNITE-DSS alone and then by the UNITE-DSS combined with the LCA module. The LCA module assesses the indirect environmental impact of the bridge itself, of the new road infrastructure accessorial to the bridge, and of the changes in travelled Vehicles-Kilometres (VKm) and Tonnes-Kilometre (TKm) due to the building of the new infrastructure.

This paper is structured as follows. Section 2 provides a brief description of the UNITE-DSS model and of the LCA module created for the purpose of the study. Section 3 describes the case study, including an overview of the NTM. Finally, the main results and conclusions from the study are discussed in the last two sections of the paper.

Nomenclature

CO ₂	Carbon Dioxide
NO _x	Nitrogen Oxides
HC	Hydrocarbons
CO	Carbon Monoxide
PM _{2.5}	Particles
SO ₂	Sulfur Oxides

2. The analytical framework

Developed based on the Danish CBA guidelines (Danish Ministry of Transport, 2015), the UNITE-DSS model is designed to provide informed decision support to decision makers by combining information provided from aggregated estimates as well as from interval results, expressed in terms of accumulated probability curves. To achieve such results the UNITE-DSS model is structured in two parts, deterministic and stochastic, as graphically depicted in Figure 1 (Salling and Leleur, 2015). The deterministic part deals with the standard CBA approach producing point estimates of common socio-economic indicators, such as Net Present Value (NPV), Benefit Cost Ratio (BCR) and Internal Rate of Return (IRR). The stochastic part produces results from the uncertainty analysis of both construction costs and transport demand forecasts, therefore producing output probability distributions (so-called certainty graphs) of the decision support indicators output of the deterministic part. The uncertainty analysis, based on Monte Carlo Simulation (MCS), is based upon the information retrieved from the UNITE Project database (UNITE, 2015), which contains information about 200 transport related projects from Scandinavian countries and UK (Nicolaisen, 2012).

To implement the analysis described in the present paper, the UNITE-DSS model has been integrated with a LCA module. The LCA module is based on a three steps process. First, it extracts from the life-cycle inventories the information related to the indirect environmental impacts, expressed in physical quantities, of the products of the case study project, i.e. the infrastructures and the vehicles. Second, it translates these impacts in monetary terms using as reference values those provided by the Danish ministry of Transport (2015). Third, it includes these environmental impacts expressed in monetary terms into the deterministic part of the UNITE-DSS model as part of the project costs (box 1 in Figure 1). The life-cycle inventories were retrieved from the well-established database Ecoinvent (2015). Ecoinvent includes a vast amount of life cycle inventories, quantifying an exhaustive number of environmental impact categories, from air polluting agents to water consumption and waste production. However, in order to consistently compare the CBA results with and without the LCA approach, for the present study the environmental impacts categories addressed by the LCA module were limited to those already included in the

UNITE-DSS, namely the air polluting agents CO₂, NO_x, HC, CO, PM_{2.5} and SO₂. With respect to the new infrastructures, the LCA module quantifies the indirect environmental impacts as a function of the amount of concrete and steel used; with respect to the vehicles, as a function of the travelled VKm (car passenger) or TKm (freight vans and lorries). Considering that the UNITE-DSS model by default only includes the air polluting agents related to vehicles emissions, the differences in the results between the two approaches, i.e. CBA with and without the LCA module, primarily represent the amount of the listed air polluting agents produced during the production, maintenance and disposal of the products of the case study project.

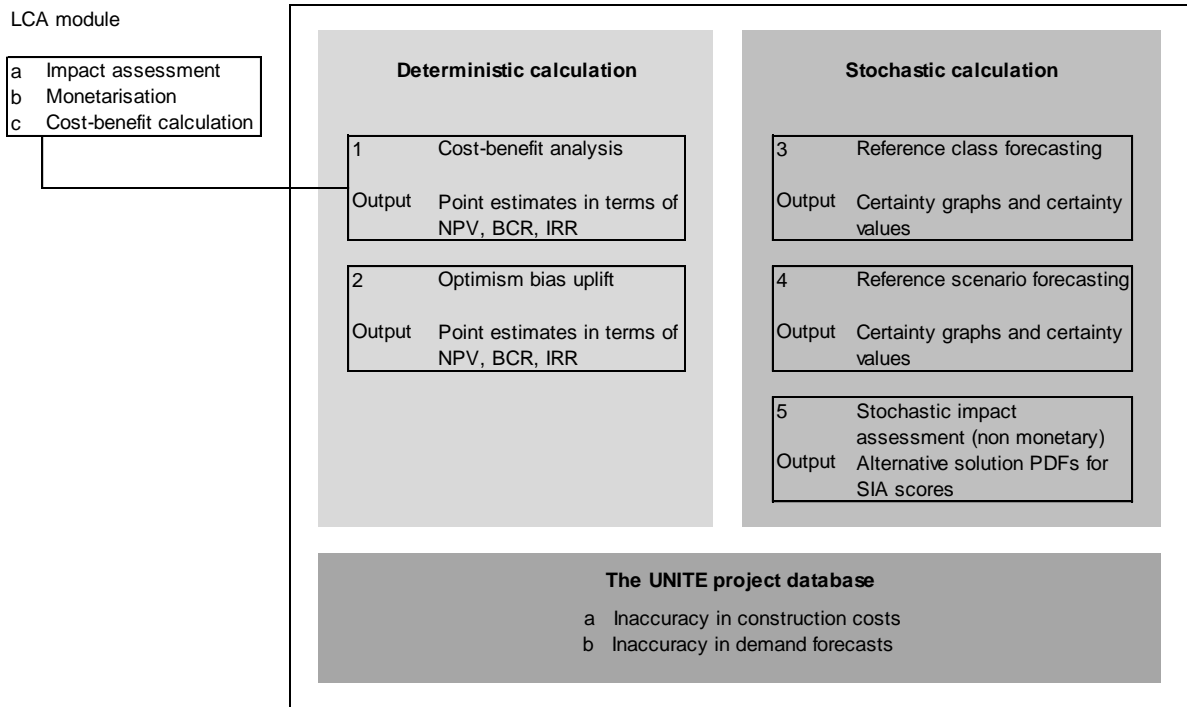


Fig. 1. The UNITE-DSS model framework.

Table 1. LCA inventories.

Product or process	CO ₂	NO _x	HC	CO	PM _{2.5}	SO ₂
Infrastructures						
Motorway	6.3562	0.0539	0.0002	0.0515	0.0046	0.0033
Bridge	1.5063	0.4065	0.0003	0.2117	0.0085	0.1020
Vehicles						
Car passenger (Petrol)	0.1154	0.0001		0.0006		
Car passenger (Diesel)	0.1137	0.0002		0.0005		
Freight vans	1.3274	0.0066		0.0129	0.0006	0.0001
Lorries	0.1280	0.0005		0.0002		

Source: Ecoinvent 2.2.

Table 1 shows the life-cycle inventories from the Ecoinvent database. With respect to the infrastructures building and maintenance, the air polluting agents are expressed in Kg per metre of infrastructure. In particular, for the bridge, the air polluting agents mainly refer to the production of the concrete and the steel required for the

construction, which counts for values between 70% and 95% of the total emissions, depending on the agents. With respect to road vehicles instead, the air polluting agents are expressed in Kg/VKm and Kg/TKm. The car passenger data refer to Euro 5 engines, so as to represent the improvement of car emissions over the length of the project evaluation (50 years).

In order to translate these quantities values into monetary units to be used to run the CBA, unit prices in Danish Kroner (DKK) per Kg were applied, as summarized in Table 2.

Table 2. Unit prices (DKK/Kg).

	CO ₂	NO _x	HC	CO	PM _{2.5}	SO ₂
Price	0.07	51.54	2.61	0.02	964.73	217.72

Source: Danish ministry of Transport.

3. The case study: the Roskilde fjord connection project

The chosen case study refers to the Roskilde Fjord new crossing project to be opened January 2020, located in Frederikssund, a Danish town of around 44,000 inhabitants at 45 minute car drive from Copenhagen. The Frederikssund municipality has a big potential for development as residential and businesses area; a new urban development project south of Frederikssund is already in the making, with plans of housing for 10,000 new inhabitants as well as 4,000 new workplaces. This area will be on the regional train line between Frederikssund and Copenhagen; furthermore, an upgrade of the road between Frederikssund and Copenhagen to a motorway scheme is an ongoing project. The volume of traffic to and from Frederikssund is high, affecting the existing Roskilde Fjord crossing, the Kronprins Frederik's bridge, connecting the peninsula of Hornsherred with the eastern part of Zealand. For these reasons, the Danish government decided to build a high level bridge crossing the Roskilde Fjord south of Frederikssund.

The planned infrastructure, shown in Figure 2, will be partially financed through user charge, while the old bridge will remain free of charge. The bridge will be 1.36 km long and 20 m wide and with a 90 km/h speed limit (Vejdirektoratet, 2010). The pedestrians and bike flows, as well as people with errands in the northern part of the city, will make use of the existing bridge, which will be downgraded to a local road. The accessory road network will have a total length of 24.2 km and a width varying between 20 m and 26 m, depending on the sections. Around 10 km of the network (including the bridge facility) will consist in a four-lane motorway.

At the time when the present analysis was implemented, detailed information about the bridge were not available. Therefore, in order to quantify the amount of concrete and steel required to build the bridge infrastructure, standard values were used instead, namely 89,000 T/Km for the concrete and 4,900 T/Km for the steel (von Rozycki et al., 2003). The bridge will have 25 pillars with a section of 1.5 m*2.1 m supported by steel pillars (Vejdirektoratet, 2010). The amount of concrete and steel required for the pillars will be high. However, no standard values were found, so the LCA for the pillars was not included into the LCA module. Unlike for the bridge and the pillars, no assumptions were required for the overall road infrastructure given that the Ecoinvent inventories are available for standard road classes.

In order to assess the effects of the planned infrastructure on traffic and derived measures, simulations were run by using the NTM (Rich et al. 2010). The NTM is a tour-based large scale transport model that combines several sub-models. Preliminarily, the model exogenous variables, such as population, transport networks and employment, are defined. Afterwards, a population matrix is created through the Prototypical Sample Enumeration (Daly, 1998) approach implemented through an iterative proportional fitting matrix estimation method. Then, the framework divides in two parallel demand models: the passenger and the freight demand models. The output of these models feeds the multimodal assignment models (including walk, bike, public transport, rail, car driver, car passenger and air), which is the last stage of the framework. The assignment models set the level of service per modes and routes by assigning traffic to the physical network at the link level. The level of service is then fed back to the passenger demand models, in an iterative process which ends when equilibrium between demand and assignment is achieved. Currently this is accomplished through a heuristic approach based on a weighted method of successive averages.



Fig. 2. The Roskilde Fjord connection project. Source: Vejdirektoratet, 2010.

The Table 3 summarises Travel Time (TT) and VKm travelled by vehicle class for the entire Denmark resulting from the comparison between the NTM output related to the 2020 base case (i.e. no bridge) and the 2020 scenario (i.e. with the bridge). The bottom part of Table 3 shows the resulting Travel Time Savings (TTS) and differences in VKm. As can be seen, while freight vans traffic is expected to experience advantages in terms of both TTS and VKm, the planned infrastructure might result in a net loss in terms of TTS and VKm for lorries, while car passengers are expected to decrease the travel time despite travelling longer distances.

Table 3. NTM 2020 output (average day).

	Car passenger	Freight vans	Lorries
Base case			
Travel time (hours)	2,163,595	134,962	199,918
VKm	125,258,509	8,374,345	13,019,412
Scenario			
Travel time (hours)	2,163,188	134,278	200,182
VKm	125,267,981	8,323,572	13,047,732
Differences			
TTS	407	684	-264
VKm	-9,472	50,773	-28,320

TTS were translated into monetary values based on different Value of Time (VoT) estimates for trip purpose and their free time and congestion time components. The VKm were used to calculate both Vehicle Operating Costs (VOC) and externalities: (i) accidents, (ii) noise, and (iii) air pollution in terms of marginal throughput values. Air pollution calculation focuses on the CO₂, NO_x, HC, CO, PM_{2.5} and SO₂ emissions. With respect to the infrastructure, the overall cost is estimated of around 2 billion DKK and the yearly maintenance costs were roughly assumed to be 2% of the construction cost per year. The opening year is planned to be 2020, based on the estimation of 5 years

construction. The evaluation period for the infrastructure is 50 years. Based on the Danish CBA guidelines, the discount ratio is 4% for the first 35 years and 3% for the remaining 15 years. Moreover, a net taxation ratio is set at 32.5% and a tax distortion ratio at 20% (Danish Ministry of Transport, 2015). The revenue from the tolls is estimated to be 26 million DKK for the opening year. The traffic on the overall network is assumed to have an annual increase of 2% for the first 20 years and then to remain constant. Based on these information and assumptions the UNITE-DSS was run twice: first without the LCA module and afterwards including the LCA module.

4. Results

Table 4 summarizes the main investment criteria resulting from the implementation of the case study. As can be noticed, the inclusion of the LCA module has a relevant impact of the final evaluation of the project. In fact, the LCA module more than doubles the (negative) value related to the external effects of the projects, from around 1.2 to around 4 billion of DKK. This results in a decrease of more than the 30% of the BCR, while the NPV and IRR of the project decrease of around 50%.

Table 4. UNITE-DSS model CBA results.

	UNITE-DSS	UNITE-DSS-LCA	Difference
Construction Costs*	-2,836	-2,836	0.00%
User benefits*	7,558	7,558	0.00%
External Effect*	-1,161	-4,015	245.77%
Operating Cost*	-1,238	-1,238	0.00%
Taxation*	2.8	2.8	0.00%
Scrap Value*	2,331	2,331	0.00%
Tax Distortion*	-428	-428	0.00%
Benefit-cost ratio	2.91	1.90	-34.71%
Internal Rate of Return	5.57%	2.82%	-50.60%
Net Present Value*	5,408	2,553	-52.78%
First Year Rate of Return	5.09%	3.26%	-35.95%

* Million DKK (2015 prices)

More in details, as graphically shown in Figure 3, when including the LCA into the UNITE-DSS model, the biggest share of the increase in the external costs of the project is due to the LCA components of the planned infrastructures, which count for around 90% of the total. The remaining 10% of the costs is instead related to the number of accidents, which stays unchanged. It is worth to notice that the costs related to the air pollution due to the vehicles decrease, going from a cost around 400 million DKK to a benefit of more than 1 billion. Therefore, it can be said that decrease of VKm travelled by Freight vans shown in Table 3, more than compensate the corresponding increase for car passenger and lorries.

The Figure 4 instead shows the same results but in comparison with the overall costs components resulting from the implementation of the CBA on the case study. Overall, by including the LCA module, the estimated costs of the project increases of 17%. As can be noticed, without the LCA module the most important cost components result to be the lorries TTS (29%) and VOC (27%), followed by the construction costs (21%). When including the LCA module, the air pollution costs component related to the new infrastructures becomes dominant, counting for 25% of the total costs, followed by lorries TTS (22%) and VOC (20%) components.

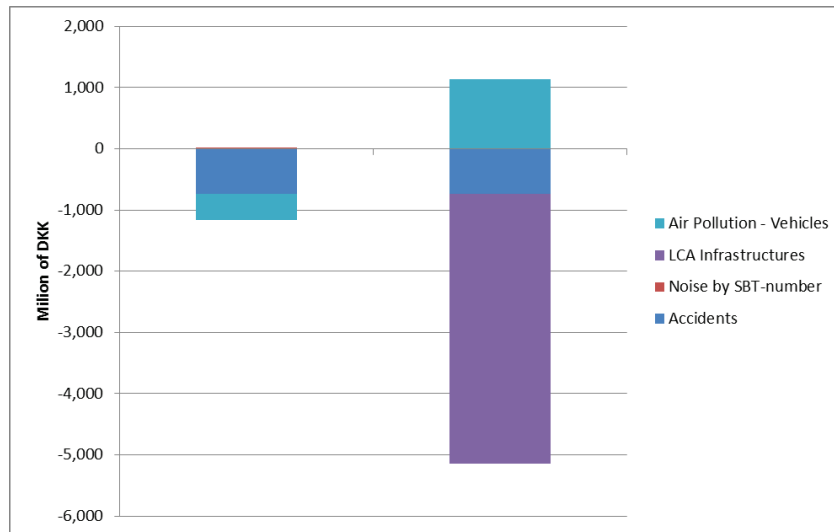


Fig. 3. Project external costs by components: the UNITE-DSS without (left column) and with (right column) LCA module.

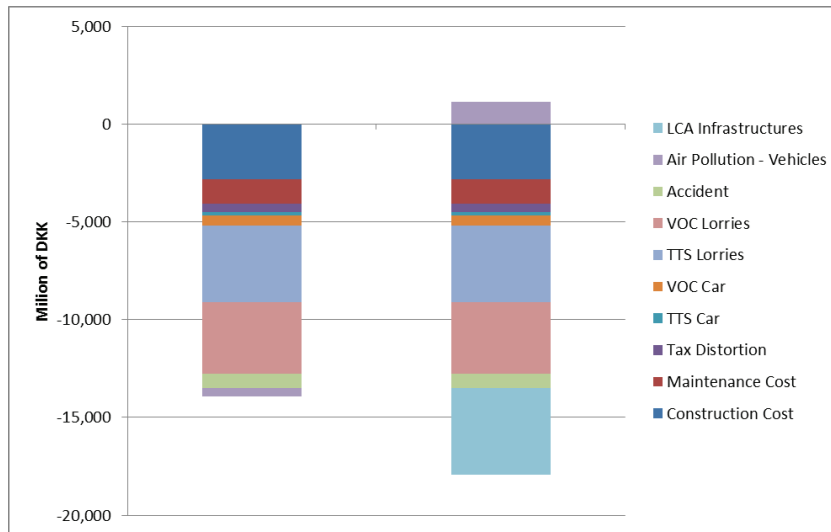


Fig. 4. Project costs by components: the UNITE-DSS without (left column) and with (right column) LCA module.

5. Conclusions

In this paper we presented the results from a study which compared the output of a transport infrastructural project CBA with and without a LCA module. Given the characteristics of the model used to run the CBA, the LCA module only added to the evaluation process the monetary cost of the air pollution impacts deriving from the building, maintenance and disposal of the planned infrastructures and of the vehicles travelling in the network. The results clearly show how the inclusion of the LCA module highly affects the socio-economic indicators output of the CBA, through the change in the estimated costs of the project. This is true both in absolute values, with an increase of 17% of the total costs, and in terms of the relative impact on the total costs of the different cost components.

The CBA results for the case study remain favourable to the project also when including the LCA module, although the LCA approach might have provided useful information to select among different typologies of infrastructures. In fact, from this point of view, the LCA can be considered fundamental to refine the optimization of the selection processes in terms of sustainability. More in general however, it seems possible to argue that for projects closer to the rejection threshold, including a LCA module might have a relevant effect on the results from the project evaluation, thus affecting the final decision. Besides, also when the socio-economic indicators stay favourable to the project, the variation in the relative weights of the cost components might lead to different decisions, for instance when an option is available which does not include the construction of a new infrastructure. However, it is important to highlight that including the LCA approach into a standard transport CBA does not always result in adding extra costs to the evaluation process. For instance, the results from the present study show how the air pollution aggregated costs deriving from the vehicles become benefits when the LCA module is included.

The present study has limitations here acknowledged by the authors. Some assumptions were needed with respect to the technical characteristics of the bridge and part of the infrastructure, specifically the pillars, was not included into the LCA module for lack of information. For comparability reasons, the LCA module did not include all the impact categories commonly present into a standard LCA analysis. Furthermore, no assumptions were made on the future market shares of electric cars, although, as shown in Table 1, the LCA components related to the manufacturing and disposal of the vehicles are only marginally affected by the type of engine. This last comment also raises some questions about the effectiveness in terms of sustainability of policies based on the increase of cleaner private vehicle market shares rather than on the reduction of private vehicles fleet.

Along with these, there is a more general issue to consider. Some of the costs considered by the LCA approach do not affect the geographical location where the project is implemented. For instance, the air pollution generated by the production of the vehicles affects the geographical area where the manufacturing process is implemented. In our case study we can exclude that the geographical location of the project analysed and that of the vehicles manufacturing coincide. In other words, the geographical perspective of the definition of sustainability we provided in the introduction does not always coincide with that of interest for the decision makers. In fact, while sustainability has a planetary boundaries dimension, a standard transport CBA has a local, sometime national boundary. Therefore the question: should the decision makers be interested in considering costs not affecting the geographical areas or populations they do not represent? One practical solution could be to include into the LCA module only the impacts affecting the project area, but this would not be consistent with the definition and meaning of sustainability and, besides, would lead to the problem of defining boundaries of the project area, not only for the LCA but also for the CBA.

However, despite the limitations, the results from the study described in the present paper suggest how indirect environmental impacts, represented by life-cycle impacts of the project components have to be included in transport project evaluations in order to properly assess long-term sustainability and provide more exhaustive information to the decision makers.

There is always space for improvements. The UNITE-DSS model allows implementing uncertainty analysis of the model variables. Such analysis was not implemented in the study described in this paper to preserve the focus on the LCA. Nevertheless, it would allow describing the uncertainty in both the CBA and the LCA module components, such as the uncertainty in the quantification and monetization of some environmental impacts, and its effects on the socio-economic indicators output of the UNITE-DSS model. With respect instead to the boundaries definition issue, specifically national boundaries, it seems worth to investigate the potential of the Economic Input-Output Life-Cycle Assessment (EIO-LCA) approach, a top-down approach based on the economic input-output tables which considers the entire economy as boundaries of the analysis (Lave et al., 1995).

Acknowledgements

The authors gratefully acknowledge the scientific support received from the members of the GDSI research center (<http://www.gdsi.dtu.dk/>) and of the SUSTAIN project (<http://www.sustain.transport.dtu.dk/english>).

References

- Chester, M.J., Horvath, A., 2013. High-speed rail with emerging automobiles and aircraft can reduce environmental impacts in California's future. *Environmental research letters*, 7, 1–11.
- Chester, M.J., Horvath, A., Madanat, S., 2010a. Comparison of life-cycle energy and emissions footprints of passenger transportation in metropolitan regions. *Atmospheric Environment*, 44, 1071–1079.
- Chester, M.J., Horvath, A., 2010b. Life-cycle assessment of high-speed rail: the case of California. *Environmental Research Letters*, 5.
- Chester, M.J., Horvath, A., 2009. Environmental assessment of passenger transportation should include infrastructure and supply chains. *Environmental Research Letters*, 4.
- Chester, M.J., Pincetl, S., Elizabeth, Z., Eisenstein, W., Matute, J., 2013b. Infrastructure and automobile shifts: positioning transit to reduce life-cycle environmental impacts for urban sustainability goals. *Environmental Research Letters*, 8, 1–10.
- Daly, A., 1998. Prototypical sample enumeration as a basis for forecasting with disaggregate models. *Transport Planning Methods*, 1(D), 225–236.
- Danish Ministry of Transport, 2015. Manual for samfundsøkonomisk analyse på transportområdet. Retrieved from: <http://www.trm.dk/da/publikationer/2015/manual-for-samfundsøkonomisk-analyse-paa-transportomraadet>.
- Ecoinvent, 2015. Database 2.2 (2010). Retrieved from: <http://www.ecoinvent.org/>.
- Eriksson, E., Blinge, M., Lovgren, G., 1996. Life cycle assessment of the road transport sector. *The Science of the Total Environment*, 189/190, 69–76.
- Hendrickson, C., Horvath, A., Joshi, S., Lave, L., 1998. Economic input-output models for environmental life-cycle assessment. *Environmental Science & Technology*, 13 (4), 184–190.
- Holden, E., Linnerud, K., Banister, D., 2013. Sustainable passenger transport: back to Brundtland. *Transportation research Part A*, 54, 67–77.
- ISO 14040, 2006. Environmental management – life cycle assessment – principles and framework. International Standards Organization, Geneva.
- Joshi, S., 2000. Product environmental life-cycle assessment using input-output techniques. *Journal of Industrial Ecology*, 3, 95–119.
- Kimball, M., Chester, M., Gino, C., Reyna, J., 2013. Assessing the potential for reducing life-cycle environmental impacts through transit-oriented development infill along existing light rail in Phoenix. *Journal of Planning Education and Research*, 33 (4), 395–410.
- Kloepffer, W., 2008. Life cycle sustainability assessment of products. *International Journal of LCA*, 13 (2), 89–95.
- Lave, L.B., Hendrikson E., McMichael, F.C., 1995. Using input-output analysis to estimate economy-wide discharges. *Environmental Science & Technology*, 9, 420–426.
- Nahlik, M.J., Chester, M.V., 2014. Transit-oriented smart growth can reduce life-cycle environmental impacts and household costs in Los Angeles. *Transport Policy*, 35, 21–30.
- Nicolaisen, M.S., 2012. Forecasts: facts of fiction? Ph.D. dissertation, Department of Planning, Aalborg University (Denmark).
- Park, K., Hwang, Y., Seo, S., Asce, M., Seo, H., 2003. Quantitative assessment of environmental impacts on life cycle of highways. *Journal of Construction Engineering and Management*, 129 (1), 25–31.
- Rich, J., Nielsen, O.A., Brems, C., Hansen, C.O., 2010. Overall design of the Danish national transport model. Paper presented at the Annual Transport Conference, Aalborg (DK).
- Salling, K.B., Leleur, S., 2015. Accounting for the inaccuracies in demand forecasts and construction cost estimations in transport project evaluation. *Transport Policy*, 38, 8–18.
- Thoft-Christensen, P., 2010. Infrastructures and life-cycle cost-benefit analysis. *Structure and Infrastructure Engineering*, 8, 507–516.
- UN, World Commission on Environment and Development, 1987. *Our Common Future*. Oxford: Oxford University Press.
- UNITE project, 2015. <http://www.unite.transport.dtu.dk/english/Project-Description>.
- Vejdirektoratet, 2015. Ny fjordforbindelse – ved Frederikssund. Sammenfattende rapport, 60–67. Retrieved from: <http://vejdirektoratet.dk/DA/vejprojekter/fjordforbindelsen/Dokumenter/Sider/default.aspx>.
- von Rozycki, C., Koeser, H., Henning, S., 2003. Ecology profile of the German high-speed rail passenger transport system, ICE. *International Journal of LCA*, 8 (2), 83–91.